

Deltaron Dibaryon Structure in Chiral $SU(3)$ Quark Model ¹

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Abstract

We discuss the structure of Deltaron dibaryon in the chiral $SU(3)$ quark model. The energy of Deltaron is obtained by considering the coupling of the $\Delta\Delta$ and CC (hidden color) channels. The effects of various parameters on the Deltaron mass are also studied. It is shown that the mass of Deltaron is lower than the mass of $\Delta\Delta$ but higher than the mass of $\Delta N\pi$.

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Searching dibaryons both theoretically and experimentally has attracted many physicists' attentions since the first theoretical prediction of H dibaryon was published by Jaffe in 1977[1]. The main reason is that because the dibaryon is a six quark system in a small region where the one-gluon-exchange and quark exchange play significant roles, it is a very good place to investigate the quark behavior in the short distance and to show the new physics on Quantum Chromodynamics (QCD). Up to now, there were lots of calculations on H dibaryon in various models[2]. A current calculation of the H dibaryon structure by using the chiral $SU(3)$ quark model [3] shows that the chiral $SU(3)$ cloud only offers a little attraction to the H dibaryon, and the energy level of the H state is around the $\Lambda\Lambda$ threshold. This result is consistent with most reports obtained recently in experiments[4]. On the other hand, the chiral $SU(3)$ quark model is quite successful not only in explaining the structures of baryon ground states but also in reproducing nucleon-nucleon ($N-N$) scattering phase shifts and hyperon-nucleon ($Y-N$) cross sections[5]. Thus, in our opinion, analyzing other possible six-quark states by using such model is quite meaningful. According to the character of the color-magnetic force in the one-gluon-exchange interaction, one found that another interesting six-quark system, named Deltaron ($S = 3, J^\pi = 3^+, T = 0$), should be studied, because its color-magnetic character does not have repulsive nature in comparison with that in the $\Delta\Delta$ state. In 1987, K.Yazaki [6] analyzed non-stranged two baryon systems in the framework of the cluster model. In his calculation, the one-gluon-exchange interaction and the confinement potential between two quarks were considered. The result

showed that in the NN , $N\Delta$ and $\Delta\Delta$ cases, only the $\Delta\Delta$ ($S = 3, T = 0$) state (Deltaron) demonstrates attractive feature. Since, Δ is a resonant state of nucleon with quite wide width and is easy to decay into $N\pi$, thus, even the Deltaron is a bound state of $\Delta\Delta$, it is still not easy to be measured in the experiment due to its large width, except Deltaron mass is lower than $NN\pi\pi$ threshold. F.Wang et.al[7] studied the structure of the Deltaron state by using the quark delocalization model. They found that the Deltaron is a deeply bound state with a binding energy of 320-390MeV, namely its energy level is even lower than the threshold of $NN\pi\pi$. However, in their calculation, the forms of the confinement potentials between all interacting quark pairs were not a unique form. Those forms depended on the situation whether these interacting quarks are in the same "baryon orbit" or in different "baryon orbits". As we know, in the Generating Coordinate Method (GCM) framework, the left centered orbit wave function and the right centered one are not orthogonal to each other, thus, in their calculation, assuming two different kind confinement potentials in one system might cause confusion.

In this paper, we calculate the energy of Deltaron by solving a coupled channel equation, $\Delta\Delta$ and CC (hidden color channel), in the framework of the Resonating Group Method (RGM) with the consideration of chiral field contributions. As is well known, in the traditional quark potential model, V_{qq} consists of two parts: the one-gluon-exchange potential (OGE) governing the short range interaction and the confinement force dominating mainly the long range interaction. This simple model achieved great success in explaining the properties of heavy quarkonia, but

met some problems in light quark systems, especially in studying the $N - N$ force. One of the problems is the source of the constituent quark mass, another is lack of medium range attraction in the $N - N$ interaction. These indicate that part of medium-range non-perturbative QCD effects is missing in this simple model. Although we do not know how to derive V_{qq} from the QCD theory vigorously, these problems can alternatively be treated by introducing constraints of chiral symmetry which is very important in the strong interaction[5]. In the chiral $SU(3)$ quark model, starting from the linear expression of the chiral- quark coupling Lagrangian, we can write the chiral-quark interaction Hamiltonian as

$$H_I^{ch} = g_{ch} \bar{\Psi} \left(\sum_{a=0}^8 \sigma_a \lambda_a + i \sum_{a=0}^8 \pi_a \lambda_a \gamma_5 \right) \Psi, \quad (1)$$

where σ_a denotes four scalar meson fields: σ , σ' , κ , and ϵ , respectively, and π_a denotes four pseudoscalar meson fields: η_1 , π , K , and η_8 , respectively, and consequently, the interaction between quarks as

$$V_{ij}^{ch} = V_{ij}^{PS} + V_{ij}^S, \quad (2)$$

with

$$V_{ij}^{PS} = C(g_{ch}, m_{\pi_a}, \Lambda) \frac{m_{\pi_a}^2}{12m_i m_j} [f_1(m_{\pi_a}, \Lambda, r_{ij})(\vec{\sigma}_i \cdot \vec{\sigma}_j) + f_2(m_{\pi_a}, \Lambda, r_{ij})S_{ij}](\lambda_i^a \lambda_j^a)_f, \quad (3)$$

$$V_{ij}^S = -C(g_{ch}, m_{\sigma_a}, \Lambda) f_3(m_{\sigma_a}, \Lambda, r_{ij})(\lambda_i^a \lambda_j^a)_f, \quad (4)$$

here V_{ij}^{PS} and V_{ij}^S are the pseudoscalar- and scalar-field induced interactions respectively. The expressions of f_i, Y, G, H , and C are shown in Ref.[5] In expressions

(3) and (4), there is only one coupling constant g_{ch} , which can be fixed by the following relation:

$$\frac{g_{ch}^2}{4\pi} = \frac{g_{NN\pi}^2}{4\pi} \frac{9}{25} \frac{m_q^2}{M_N^2}. \quad (5)$$

Then, the Hamiltonian of the chiral $SU(3)$ quark model reads,

$$H = \sum_i T_i - T_G + \sum_{i < j} V_{ij}, \quad (6)$$

where V_{ij} includes one-gluon-exchange interaction, confinement potential and chiral-quark field coupling induced interactions,

$$V_{ij} = V_{ij}^{OGE} + V_{ij}^{conf} + V_{ij}^{ch}. \quad (7)$$

In Equation (7), V_{ij}^{OGE} is taken in the usual form and V_{ij}^{conf} is chosen to be a quadratic form used in Ref.[5]

$$V_{ij}^{conf} = -(\lambda_i^a \lambda_j^a)_c (a_{ij} r_{ij}^2 + a_{ij} 0). \quad (8)$$

The coupling constant of OGE and the strength of confinement potential are determined by the stability condition of nucleon and the mass difference between Δ and N [3, 5].

From the analysis in Ref.[8], we know that the model space of a simple $(0s)^6$ six-quark-cluster configuration is not large enough to describe the dibaryon structure sufficiently. It is more effective to choose the two-cluster configuration as the dibaryon's model space. According to Ref.[9], the basis of two clusters (i.e physical basis) and the six-quark cluster (i.e. symmetry basis) for the case of $S = 3, T = 0$ have certain relation. We show it in Table 1. In the table, CC channel is the

Table 1: Coefficients between the physical basis states
and the symmetry basis states

| | $[6][33]_{30}$ | $[42][33]_{30}$ |
|-----------------------|----------------------|-----------------------|
| $(\Delta\Delta)_{30}$ | $\sqrt{\frac{1}{5}}$ | $\sqrt{\frac{4}{5}}$ |
| $(CC)_{30}$ | $\sqrt{\frac{4}{5}}$ | $-\sqrt{\frac{1}{5}}$ |

hidden color state which has the form of,

$$|CC\rangle_{S=3,T=0} = -\frac{1}{2} |\Delta\Delta\rangle_{S=3,T=0} + \frac{\sqrt{5}}{2} A_{STC} |\Delta\Delta\rangle_{S=3,T=0}, \quad (9)$$

where A_{STC} is the antisymmetrization operator in the spin-isospin-color space.

In this work, we choose a model space where both $\Delta\Delta$ and CC channels are included. The mixture of the $L = 0$ and $L = 2$ states which shows the effects of the tensor forces from OGE and chiral field coupling are also included, namely two channels with four states, $\Delta\Delta(L = 0)$, $\Delta\Delta(L = 2)$, $CC(L = 0)$ and $CC(L = 2)$ are considered. The corresponding matrix elements of spin-isospin-color operators are given in Appendix.

In the coupled channel bound state calculation, one must carefully eliminate the forbidden states which may spoil the numerical calculation. In the Deltaron case, there exists a state with the zero eigenvalue of the normalization operator, $\langle N \rangle = 0$, because of the Pauli blocking effect. It reads

$$|\Psi\rangle_{forbidden} = |\Delta\Delta\rangle - \frac{1}{2} |CC\rangle. \quad (10)$$

To obtain the reliable result, we perform the off-shell transformation to eliminate those non-physical degrees.

In the calculation, the same set of model parameters which can reproduce N-N scattering phase shifts and Y-N cross sections[5] are employed. We present the calculated the Deltaron energy and the root-mean-square radius (RMS) in the chiral $SU(3)$ quark model in Table 2. For comparison, we also show the results with OGE only and OGE plus π, σ fields (namely chiral $SU(2)$ coupling) with four cases, $\Delta\Delta(L=0)$, $\Delta\Delta(L=0+L=2)$, $\Delta\Delta+CC(L=0)$ and $\Delta\Delta+CC(L=0+L=2)$. From Table 2, we see that the energy of Deltaron is indeed lower than two Δ s', but it is not a deeply bound state. Its binding energy is always several tens MeV in all three different cases: the OGE , $OGE+SU(2)$ and $OGE+SU(3)$ cases. Since the Deltaron energy is still higher than the mass of $N\Delta\pi$, it is not a narrow width dibaryon.

The channel coupling effect is more significant than the L state mixing effect due to the tensor interaction. The energy of Deltaron in the case of $OGE+SU(2)$ is the lowest one. This means that the π and σ chiral fields can offer attractions and make the Deltaron more bound against $\Delta\Delta$. However, the total effect of $SU(3)$ chiral fields would not be able to make the Deltaron energy lower further.

Table 2: Energy and RMS of Deltaron dibaryon*

| | | $\Delta\Delta(L=0)$ | $\Delta\Delta \begin{pmatrix} L=0 \\ +2 \end{pmatrix}$ | $\Delta\Delta_{CC}(L=0)$ | $\Delta\Delta_{CC} \begin{pmatrix} L=0 \\ +2 \end{pmatrix}$ |
|--------------------|-------------------|---------------------|--|--------------------------|---|
| OGE | $B \text{ (MeV)}$ | 29.8 | 29.9 | 41.0 | 42.0 |
| | $\bar{R}(fm)$ | 0.92 | 0.92 | 0.87 | 0.87 |
| OGE+ π, σ | $B \text{ (MeV)}$ | 50.2 | 62.6 | 68.6 | 79.7 |
| | $\bar{R}(fm)$ | 0.87 | 0.86 | 0.84 | 0.83 |
| OGE+SU(3) | $B \text{ (MeV)}$ | 18.4 | 22.5 | 31.7 | 37.3 |
| | $\bar{R}(fm)$ | 1.01 | 1.00 | 0.92 | 0.92 |

$$^*B = -(E_{Deltaron} - 2M_{\Delta})$$

$$\bar{R} = \sqrt{\langle r^2 \rangle}$$

On the other hand, we investigate the influence of parameter values on the Deltaron energy. We first examine the effect from the mass of σ . In general, the σ mass can be estimated according to the following relation [10]

$$m_\sigma^2 = (2m_q)^2 + m_\pi^2. \quad (11)$$

Therefore, taking m_σ to be $600\text{--}700\text{MeV}$ is reasonable. In Table 2, we choose $m_\sigma = 625\text{MeV}$, which is the same as that used in Ref.[5]. For comparison, the results with $m_\sigma = 550\text{MeV}$ which is a case in limit are also tabulated in Table 3. From this table, one sees that the results do not change much even m_σ is reduced to a smaller value. Then, we study the influence of the baryon size parameter b_N which greatly affects the confinement strength. In the N-N scattering calculation, b_N is chosen to be 0.505fm , the corresponding confinement strength is $a_c = 54.34\text{MeV}/\text{fm}^2$ [5]. Here, we take another set of parameters where $b_N = 0.60\text{fm}$ and corresponding $a_c = 8.19\text{MeV}/\text{fm}^2$ to show the effect from the confinement strength. The result is also given in Table 3. It is noted that the influence from different b_N is small.

As we know, the form of the confinement potential and the confinement strength only slightly affect the calculated scattering and bound state results in the two-color-singlet-cluster system. Now, to study the Deltaron structure, we have to include the hidden-color channel CC to enlarge the model space. However, once the CC channel is considered, there would exist the color Van der Waals force problem. To solve this puzzle, the authors in Ref[11] used an error-function-like confinement potential to account for the color screening effect, namely the non-perturbative QCD effect. Therefore, it is necessary to examine whether the hidden-color state

Table 3: Deltaron energy B(MeV) with different parameters*

| | $(\Delta\Delta + CC) \ (L = 0 + L = 2)$ | | | |
|--------------------|---|------|-------|-------|
| OGE+ π, σ | 79.7 | 97.1 | 97.9 | 113.4 |
| OGE+SU(3) | 37.3 | 64.2 | 52.4 | 79.2 |
| $b_N(fm)$ | 0.505 | 0.60 | 0.505 | 0.60 |
| $m_\sigma(MeV)$ | 625 | 625 | 550 | 550 |

$$^*B = -(E_{Deltaron} - 2M_\Delta)$$

in the bound state calculation is sensitive to the form of the confinement potential.

For this purpose, we also adopt the error-function-like confinement potential

$$V_{ij}^{erf-conf} = -(\lambda_i \cdot \lambda_j)_c (a_{ij0} + a_{ij} erf(\frac{r}{csl})), \quad (12)$$

where csl is the color screening length taken to be $2.0fm$ to calculate the Deltaron structure. The results are shown in Table 4. From the table, one sees that the energy and RMS of Deltaron are quite similar to those in the quadratic confinement case, namely these bound state properties vary not much as the color screening effect is accounted. The stabilities of these results reflect the reliability of our calculation.

We finally conclude that in the framework of the chiral $SU(3)$ quark model, the binding energy of the Deltaron is stably ranged around several tens MeV even we vary the mass of σ and the baryon size parameter in the reasonable regions and change the form of the confinement to the error-function-like form to include

Table 4: Energy and RMS of Deltaron with error-function-like confinement*

| | | $\Delta\Delta(L=0)$ | $\Delta\Delta \begin{pmatrix} L=0 \\ +2 \end{pmatrix}$ | $\Delta\Delta_{CC}(L=0)$ | $\Delta\Delta_{CC} \begin{pmatrix} L=0 \\ +2 \end{pmatrix}$ |
|--------------------|-------------------|---------------------|--|--------------------------|---|
| OGE | $B \text{ (MeV)}$ | 20.9 | 21.0 | 38.1 | 39.1 |
| OGE+ π, σ | $B \text{ (MeV)}$ | 44.4 | 56.8 | 71.4 | 81.8 |
| OGE+SU(3) | $B \text{ (MeV)}$ | 13.3 | 17.5 | 32.5 | 38.1 |

$$^*B = -(E_{Deltaron} - 2M_\Delta)$$

$$\bar{R} = \sqrt{\langle r^2 \rangle}$$

the color screening effect, except in the case of OGE+ π, σ with $b_N = 0.6fm$ and $m_\sigma = 550MeV$, where the binding energy of Deltaron is about $113MeV$. This means that the mass of Deltaron is always lower than that of $\Delta\Delta$, but higher than that of $\Delta N\pi$. As a conclusion, we see that although the model space has been enlarged, the color screening effect has been considered and the contributions from various chiral fields have been included, the binding energy of Deltaron is always remained around several tens MeV . Thus, we announce that there does not exist a deeply bound Deltaron dibaryon state with narrow width.

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APPENDIX

Table 5: Coefficients of spin-flavor-color operators

| \hat{O}_{ij} | | $\Delta\Delta$ | $\Delta\Delta$ | CC | \hat{O}_{ij} | | $\Delta\Delta$ | $\Delta\Delta$ | CC |
|--|----------------------|----------------|----------------|----------------|--|----------------------|----------------|----------------|---------------|
| | | $\Delta\Delta$ | CC | CC | | | $\Delta\Delta$ | CC | CC |
| | 1 | 27 | 0 | 27 | | \hat{O}_{ij} | 9 | 0 | 9 |
| | P_{36} | -3 | -12 | -21 | $\vec{\sigma}_i \cdot \vec{\sigma}_j$ | $\hat{O}_{ij}P_{36}$ | -1 | -4 | -7 |
| $\lambda_i^c \cdot \lambda_j^c$ and $(\vec{\sigma}_i \cdot \vec{\sigma}_j)(\lambda_i^c \cdot \lambda_j^c)$ | \hat{O}_{12} | -72 | 0 | -18 | $\sum_{k=1}^3 \lambda_i^F(k) \lambda_j^F(k)$ and $(\vec{\sigma}_i \cdot \vec{\sigma}_j)(\sum_{k=1}^3 \lambda_i^F(k) \lambda_j^F(k))$ | \hat{O}_{12} | 9 | 0 | -9 |
| | \hat{O}_{36} | 0 | 0 | -36 | | \hat{O}_{36} | -15 | 0 | -3 |
| | $\hat{O}_{12}P_{36}$ | 8 | 32 | 2 | | $\hat{O}_{12}P_{36}$ | -1 | -4 | 11 |
| | $\hat{O}_{13}P_{36}$ | 8 | 32 | 20 | | $\hat{O}_{13}P_{36}$ | -1 | -4 | 5 |
| | $\hat{O}_{16}P_{36}$ | 8 | -4 | 20 | | $\hat{O}_{16}P_{36}$ | -1 | 8 | 5 |
| | $\hat{O}_{14}P_{36}$ | -4 | 2 | 35 | | $\hat{O}_{14}P_{36}$ | 3 | 6 | 0 |
| | $\hat{O}_{36}P_{36}$ | -16 | 8 | 32 | | $\hat{O}_{36}P_{36}$ | 7 | 4 | 1 |
| factor | | $\frac{1}{27}$ | $\frac{1}{27}$ | $\frac{1}{27}$ | factor | | $\frac{1}{9}$ | $\frac{1}{9}$ | $\frac{1}{9}$ |

Table 6: Coefficients of spin-flavor-color operators(tensor part)

| \hat{O}_{ij} | | $\Delta\Delta$ | $\Delta\Delta$ | CC | \hat{O}_{ij} | | $\Delta\Delta$ | $\Delta\Delta$ | CC |
|---|-----------------------|------------------------------------|------------------------------------|------------------------------------|--|-----------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| | | $\Delta\Delta$ | CC | CC | | | $\Delta\Delta$ | CC | CC |
| $(\vec{\sigma}_i \vec{\sigma}_j)_2$ | \hat{O}_{ij} | 54 | 0 | 54 | | | | | |
| | $\hat{O}_{ij} P_{36}$ | -6 | -24 | -42 | | | | | |
| $(\vec{\sigma}_i \vec{\sigma}_j)_2 (\lambda_i^c \cdot \lambda_j^c)$ | \hat{O}_{12} | -144 | 0 | -36 | $(\vec{\sigma}_i \vec{\sigma}_j)_2 (\sum_{k=1}^3 \lambda_i^F(k) \lambda_j^F(k))$ | \hat{O}_{12} | 18 | 0 | -18 |
| | \hat{O}_{36} | 0 | 0 | -72 | | \hat{O}_{36} | -30 | 0 | -6 |
| | $\hat{O}_{12} P_{36}$ | 16 | 64 | 4 | | $\hat{O}_{12} P_{36}$ | -2 | -8 | 22 |
| | $\hat{O}_{13} P_{36}$ | 16 | 64 | 40 | | $\hat{O}_{13} P_{36}$ | -2 | -8 | 10 |
| | $\hat{O}_{16} P_{36}$ | 16 | -8 | 40 | | $\hat{O}_{16} P_{36}$ | -2 | 16 | 10 |
| | $\hat{O}_{14} P_{36}$ | -8 | 4 | 70 | | $\hat{O}_{14} P_{36}$ | 6 | 12 | 0 |
| | $\hat{O}_{36} P_{36}$ | -32 | 16 | 64 | | $\hat{O}_{36} P_{36}$ | 14 | 8 | 2 |
| factor | | $\frac{1}{27} \sqrt{\frac{14}{5}}$ | $\frac{1}{27} \sqrt{\frac{14}{5}}$ | $\frac{1}{27} \sqrt{\frac{14}{5}}$ | factor | | $\frac{1}{9} \sqrt{\frac{14}{5}}$ | $\frac{1}{9} \sqrt{\frac{14}{5}}$ | $\frac{1}{9} \sqrt{\frac{14}{5}}$ |

and

$$\begin{aligned}
 \langle \lambda_i^F(8) \lambda_j^F(8) \rangle &= \frac{1}{3} \langle 1 \rangle \\
 \langle (\vec{\sigma}_i \cdot \vec{\sigma}_j) (\lambda_i^F(8) \lambda_j^F(8)) \rangle &= \frac{1}{3} \langle \vec{\sigma}_i \cdot \vec{\sigma}_j \rangle \\
 \langle (\vec{\sigma}_i \vec{\sigma}_j)_2 (\lambda_i^F(8) \lambda_j^F(8)) \rangle &= \frac{1}{3} \langle (\vec{\sigma}_i \vec{\sigma}_j)_2 \rangle
 \end{aligned}$$